

The isotensor pentaquark¹

Philip R. Page

Theoretical Division, MS B283, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract. Further consequences of the 1540 MeV Θ^+ resonance as an isotensor pentaquark beyond Capstick *et al.* [1] are explored. It is argued that the SAPHIR data may not currently exclude the existence of the charged partner Θ^{++} . The usual prediction of the dominance of non-resonant Θ^+K , and Θ^+K^* , final states in photoproduction on the proton is argued not to obtain for an isotensor Θ^+ . This enhances the importance of excited baryon final states, where the excited baryon decays to Θ^+K or Θ^+K^* ; as well as the non-resonant $\Theta^+K\pi$ final state. The small width of the recently discovered Ξ^{--} cascade resonance to $\Xi^-\pi^-$ is easier to explain if Θ^+ is an isotensor pentaquark than if it is in the $\mathbf{\bar{10}}$ representation, due to both an isospin and U-spin selection rule. A new production diagram for Θ^+ in the photoproduction on the deuteron is suggested.

AN ISOTENSOR PENTAQUARK EXPLAINS THE Θ^+ WIDTH

The consensus of various experiments is that the total width Γ of Θ^+ is less than 9 MeV [1]. More restrictive bounds on the width emerge from its non-observation in K^+d scattering ($\Gamma < 6$ MeV) [2] and K^+ -nucleon scattering ($\Gamma \lesssim 1$ MeV) [3]. It was proposed that the narrowness of the Θ^+ can be explained if it is an isotensor state, in which case the decay to the kinematically allowed channels nK^+ and pK^0 is isospin violating [1]. Based on this hypothesis, an upper bound of roughly 0.45 MeV was put on the width [1], consistent with all experimental data above. If Θ^+ is isotensor, other charge states like Θ^{++} should exist.

SAPHIR MAY NOT HAVE EXCLUDED THE EXISTENCE OF Θ^{++}

In addition to the observation by SAPHIR of the Θ^+ with 63 ± 13 events, they also see a statistically insignificant Θ^{++} signal with 75 ± 35 events in the reaction $\gamma p \rightarrow \Theta^{++}K^- \rightarrow pK^+K^-$ [4]. The SAPHIR detector appears to have an acceptance² that is about eight times higher in K^+K^-p than in $K^+K_S^0n$. An estimate for the ratio of cross-sections for Θ^{++} and Θ^+ production is then³

¹ Expanded version of a talk presented at the X International Conference on Hadron Spectroscopy (HADRON '03), 31 Aug. - 6 Sept., Aschaffenburg, Germany.

² SAPHIR estimates an acceptance ratio of 5000 events / 63 events / $(3 \text{ to } 4) \times 1/2 \times 2/3 = 7.6$ [4].

³ Noting that the observed K_S^0 is only produced half the time from \bar{K}^0 and that the detected $\pi^+\pi^-$ mode of K_S^0 has a branching ratio of about 2/3. The branching ratio $Br(\Theta^{++} \rightarrow pK^+)$ is very close to unity if Θ^{++} is below the $NK\pi$ threshold [1].

$$\frac{\sigma(\gamma p \rightarrow \Theta^{++} K^-)}{\sigma(\gamma p \rightarrow \Theta^+ \bar{K}^0)} = \frac{1}{2} \frac{2}{3} \frac{1}{8} \frac{N(\Theta^{++})}{N(\Theta^+)} \frac{Br(\Theta^+ \rightarrow n K^+)}{Br(\Theta^{++} \rightarrow p K^+)} \leq \frac{1}{24} \frac{75 \pm 35}{63 \pm 13} = \frac{1}{20 \pm 10}. \quad (1)$$

Thus the process $\gamma p \rightarrow \Theta^{++} K^-$ is at least 20 ± 10 times weaker than $\gamma p \rightarrow \Theta^+ \bar{K}^0$. The cross-section $\sigma(\gamma p \rightarrow \Theta^+ \bar{K}^0)$ was measured to be 200 nb [4]. A preliminary analysis by CLAS in the *same* reaction with the *same* photon energy range does not see the Θ^+ and gives a cross-section < 20 nb [5]. If the CLAS result is correct, then the serious discrepancy suggests that the SAPHIR analysis may well be in error, and the existence of the Θ^{++} is not excluded.

The photoproduction of an isotensor Θ through the process $\gamma p \rightarrow K \Theta$ cannot proceed via isospin conserving interactions through the isoscalar component of the photon, so that the process is taken to proceed through the isovector component (usually associated with the ρ^0 via vector meson dominance) [1] or the smaller isotensor component T^0 arising from four-quark Fock states. If $\gamma = c_0 |I=0\rangle + c_1 |I=1\rangle + c_2 |I=2\rangle$ the scattering T-matrix element

$$\begin{aligned} \langle \gamma p | T | \Theta K \rangle &= \sum_n \langle \gamma p | n \rangle \langle n | T | \Theta K \rangle = \\ &c_1 \left\langle \frac{3}{2} \frac{1}{2} \middle| 2 I_\Theta^z \frac{1}{2} I_K^z \right\rangle \sum_n \langle \rho^0 p | n \rangle \langle n | T | \Theta K \rangle_R + c_2 \sum_n \langle T^0 p | n \rangle \langle n | T | \Theta K \rangle \end{aligned} \quad (2)$$

where a formal sum over asymptotic states n has been inserted. The Clebsch-Gordon coefficient has been isolated explicitly from the $\langle n | T | \Theta K \rangle$ overlap corresponding to the $I=1$ photon component, noting that only intermediate states with $I=3/2$ can contribute in this case, and assuming that strong interactions conserve isospin. If the isotensor component of the photon is negligible, as is usually assumed, the amplitude ratio for scattering to Θ^+ ($I_\Theta^z = 0$) and Θ^{++} ($I_\Theta^z = 1$) is $\langle \frac{3}{2} \frac{1}{2} | 20 \frac{1}{2} \frac{1}{2} \rangle / \langle \frac{3}{2} \frac{1}{2} | 21 \frac{1}{2} - \frac{1}{2} \rangle = -\sqrt{\frac{2}{3}}$. The Θ^+ is produced with a cross-section $2/3$ that of Θ^{++} (the SAPHIR calculation obtained a factor of $1/3$ [4]). In Eq. 1 this ratio was estimated to be 20 ± 10 , which led SAPHIR to conclude that Θ^{++} does not exist [4].

ISOTENSOR Θ^+ PHOTOPRODUCTION ON THE NUCLEON

Photoproduction of Θ^+ on the nucleon is typically calculated in hadronic models because perturbative QCD is not applicable [6]. However, in any of these models diagrams are missing, e.g. the *a priori* important proton sea diagram in Fig. 1, and there is a proliferation of unknown coupling constants. It is therefore instructive to return to a naïve quark level discussion understanding that the diagrams are not those of perturbative QCD, but represent Green's functions needed to evaluate the scattering T-matrix. The discussion will assume that there is a penalty for each time a quark-antiquark pair needs to be created from the vacuum.

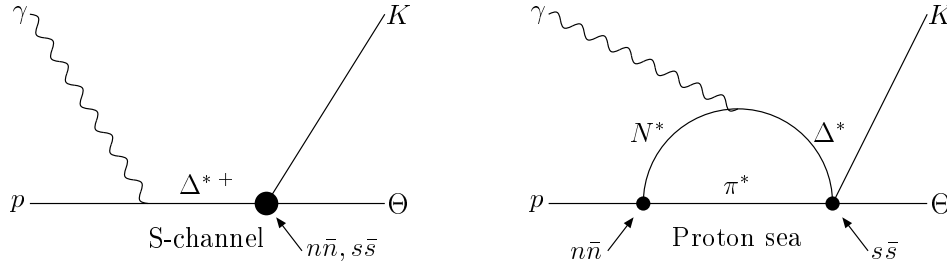


FIGURE 1. S-channel and proton sea production. An asterisk indicates an off-shell particle with the flavor structure of the corresponding on-shell particle. The site of pair creation is indicated by a filled circle, and the pair(s) that is created is shown. In the S-channel diagram the photon interacts first, and the two pairs are created later. In the proton sea diagram the light quark $n\bar{n}$ pair is created first, the photon subsequently interacts, and the strange quark $s\bar{s}$ pair is created last.

Consider the generic process $\gamma N \rightarrow K^* \Theta^+$ for an isotensor Θ^+ . Here K^* represents either the ground state K or an excited state with the flavor of K . In order for the process to happen, one light quark $n\bar{n} \equiv (u\bar{u} + d\bar{d})/\sqrt{2}$ pair and one $s\bar{s}$ pair must be created. The dominant production process is expected to be where one of the pairs that need to be created is created by the photon. (Such production processes can be found in the T-channel mechanisms suggested in Fig. 4 of Ref. [7], Fig. 1 of Ref. [4] and Refs. [6].) Because the isoscalar component of the photon does not contribute within isospin conserving interactions, this can only be the $n\bar{n}$ pair. The $s\bar{s}$ pair will then be created from gluons. The three light quarks in the incoming N will directly go into the outgoing Θ^+ . However, this is isospin forbidden: the three light quarks in the Θ^+ is isospin $3/2$, and the N is isospin $1/2$. Since the would-be dominant production process vanishes within isospin symmetry, the production of the Θ^+ is more complicated. The photon interacts with a quark or antiquark, but the two $q\bar{q}$ pairs are both created from gluons.

$\gamma N \rightarrow K \Theta^+$ [4]: For this process intermediate resonance mechanisms of the type $\gamma N \rightarrow \Delta^* \rightarrow K \Theta^+$ should be considered (similar to the S-channel diagram in Fig. 1). (An intermediate N^* is not allowed by isospin conservation.) The production process $\gamma N \rightarrow \Delta^*$ requires no pair creation, while the decay $\Delta^* \rightarrow K \Theta^+$ requires two pair creations, and has to compete with the various decay modes to a baryon and meson. There are also non-resonant mechanisms which require two pair creations, for example the proton sea diagram in Fig. 1. Hence the $\gamma N \rightarrow \Delta^*$ and non-resonant $K \Theta^+$ mechanisms are competitive.

$\gamma N \rightarrow K \Theta^+ \pi$ [7]: Since the $\gamma N \rightarrow K^* \Theta^+$ process requires two pair creations from the isospin selection rule explicated above, other processes become competitive. (The branching ratio $K^* \rightarrow K \pi$ is close to unity so that the pair creation needed for the decay incurs no penalty). Generally the process $\gamma N \rightarrow K \Theta^+ \pi$ can happen by creating two $n\bar{n}$ pairs and one $s\bar{s}$ pair. This can only be competitive with the $\gamma N \rightarrow K^* \Theta^+$ process if the photon creates one of the pairs. Processes with intermediate resonances of the type $\gamma N \rightarrow \Delta^* \pi$ with $\Delta^* \rightarrow K \Theta^+$ can happen via the photon creating an $n\bar{n}$ pair, with n going into the Δ^* , and \bar{n} going into the π . Such a process involves two pair creations

from the vacuum in the decay $\Delta^* \rightarrow K\Theta^+$. Another possibility is $\gamma N \rightarrow \Delta^*$ where $\Delta^* \rightarrow K^*\Theta^+$ which again requires two pair creations for the decay. There are also non-resonant mechanisms which require two pair creations from the vacuum. (There are even non-resonant mechanisms coming from a four-quark Fock component in the photon, including a possible isotensor component, with *one* pair creation from the vacuum.) Hence the $\gamma N \rightarrow \Delta^*\pi$, Δ^* , and non-resonant $K^*\Theta^+$ and $K\Theta^+\pi$ mechanisms are competitive.

THE Ξ^{--} AND ISOTENSOR Θ^+ CAN BE CONSISTENT

The recently discovered Ξ^{--} [8] can be put in the same $SU_F(3)$ multiplet as the Θ^+ if both are pentaquarks. An isotensor Θ^+ can only be put in a **35** representation of $SU_F(3)$ (mentioned in Ref. [9]), while an isoscalar Θ^+ can only be put in the $\bar{\mathbf{10}}$ representation. Both these representations also admit Ξ^{--} . In both representations the Θ^+ and Ξ^{--} are in the same V-spin multiplet. V-spin is an exact quantum number if $SU_F(3)$ is an exact symmetry of QCD. The p and Ξ^- are in the same V-spin multiplet and $SU_F(3)$ representation. Similarly for the K^0 and π^- . Hence the decay amplitude $\Theta^+ \rightarrow pK^0$ and that of $\Xi^{--} \rightarrow \Xi^-\pi^-$ are related by a V-spin Clebsch-Gordon relation. If the Θ^+ is isotensor the decay amplitude to pK^0 is zero within isospin symmetry. The V-spin relation implies that the decay amplitude $\Xi^{--} \rightarrow \Xi^-\pi^-$ is zero within $SU_F(3)$ symmetry. If the Θ^+ is isoscalar neither the Θ^+ nor the Ξ^{--} decay amplitudes are zero by these symmetry arguments.

The decay $\Xi^{--} \rightarrow \Xi^-\pi^-$ is also suppressed by a U-spin selection rule if Θ^+ is isotensor, but not if it is isoscalar. U-spin is an exact quantum number if $SU_F(3)$ is an exact symmetry of QCD. The U-spin of Ξ^{--} is 2 and 0 in the **35** and $\bar{\mathbf{10}}$ representations respectively. The U-spin of Ξ^- and π^- is 1/2. The decay $\Xi^{--} \rightarrow \Xi^-\pi^-$ is hence U-spin forbidden only if Ξ^{--} is in the **35** representation, noting that this “fall-apart” decay proceeds without quark pair creation, i.e. the interaction is a U-spin singlet.

The fact that the decay $\Xi^{--} \rightarrow \Xi^-\pi^-$ is suppressed by two independent symmetry arguments if Θ^+ is isotensor goes a long way towards explaining the small < 18 MeV total width of Ξ^{--} [8]. The fly in the ointment is that Ξ^{--} can also decay to $\Xi^{*-}\pi^-$ and Σ^-K^- via fall-apart decay, and to $\Xi\pi\pi$ and $\Sigma K\pi$ via one vacuum $n\bar{n}$ pair creation. It remains to be explained why these decay widths are small.

PHOTOPRODUCTION THROUGH THE π IN THE DEUTERON

In the reaction $\gamma d \rightarrow p(n)K^+K^-$ studied at CLAS [10] the p and K^- must be detected in order to reconstruct the final state. If the p is a spectator, it will not be seen due to its small kinetic energy [10]. Only K^- which are not produced forward can be detected. Hence diagrams were suggested that are not of a spectator nature [10, 11]. The $KN \rightarrow \Theta^+$ fusion diagram of Ref. [11] is not allowed for an isotensor Θ^+ due to isospin conservation. The diagram originally suggested involved a $\gamma n \rightarrow \Theta^+K^-$ vertex [10], which was shown above to require two vacuum pair creations for an isotensor Θ^+ , and

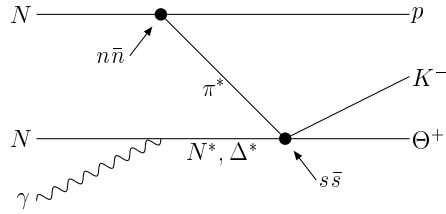


FIGURE 2. Photoproduction of Θ^+ on the deuteron. The neutron and proton in the deuteron are denoted by N . There are diagrams for each possible assignment of the neutron and proton to the label N . The other conventions are as in Fig. 1.

a K^- rescattering on the photon. In Fig. 2 a diagram is displayed which requires two vacuum pair creations and no rescattering, and should hence be dominant. The diagram is natural because the deuteron is an extended nucleus mainly bound by long-distance π -exchange.

ACKNOWLEDGMENTS

The help of both W. Roberts and S. Capstick (construction of the **27** and **35** multiplets), W. Roberts (noting the isotensor component of the photon), D. Weygand (noting the excited baryon production), and detailed discussions with L. Guo, K. Hicks and D. Weygand on their experimental data, are acknowledged. Additional helpful discussions with B. L. Berman, P. Bicudo, B. Cahn, A. Dolgolenko, T. Goldman, E. Klempt, H. J. Lipkin, C. A. Meyer, R. Schumacher, S. Sasaki, S. Stepanyan and M. Wagner are gratefully acknowledged. This research is supported by the U.S. Department of Energy under contract W-7405-ENG-36.

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